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Application of wave guide propagation to selection of transmitter power and frequency

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This paper is concerned with developing reasonable criteria for the selection of frequency and power for very low and low-frequency (VLF/LF) transmitting stations. The approach uses a wave guide model for low-frequency propagation and accounts for the variability of the ionosphere. A sample problem involving a hypothetical transmitter is described

INTRODUCTION

VLF/LF radio signals are subject to vector interference phenomena that can produce deep minima in the signal strength simultaneously with rapid shifts of the phase of the signal. These signal minima are called modal interference nulls because they occur as the result of destructive interference between modes propagating in the Earth-ionosphere wave guide. These nulls are observed when the signal amplitude is recorded as a function of time, distance, or frequency within the VLF/LF band. These interference phenomena can be detrimental to VLF/LF communication systems.

The signal level varies with time primarily because of variations in the ionosphere. Positions of the modal interference minima also fluctuate. The position of a null is generally more stable during normal daytime propagation conditions than it is during the night. However, when an ionospheric disturbance occurs, such as those caused by solar flares, the nulls may move a 100 km or may disappear completely. Calculation of signal strength at a given location is made difficult because it is a nonlinear function of the parameters used to describe the Earth-ionosphere wave guide. Hence it is difficult to present simple general conditions for selecting transmitter factors such as the required radiated power. In deriving power requirements which would result in satisfactory communications with a designated time availability at all times of day, it is common to use a worst case approach. Thus the power requirement is based on the condition which results in the lowest expected signal-to-noise ratio (snr). Unfortunately, this worst case approach usually yields very high power requirements, especially when the effect of modal propagation nulls is considered. However, the deep nulls affect only small geographic areas during the daytime, and the impact on the power required can be reduced (derated) by neglecting the small percentage of the operational area affected. With this technique, which will be referred to as null smoothing, reasonable radiated power requirements can be derived.

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PROPAGATION PREDICTION MODEL

In the propagation model employed in this analysis, radio waves are considered to propagate in a wave guide defined by the space between the Earth and the ionosphere. The model is based on *Budden* [1961] and was first described by *Pappert et al.* [1967]. In this model both boundaries of the wave guide may vary arbitrarily over the transmission path. These variations are treated as a series of horizontally homogeneous segments. Within each segment the ionosphere is characterized by arbitrary electron and ion density distributions and collision frequencies as functions of height. The lower boundary is considered to be a smooth and vertically homogeneous Earth which is described by its surface conductivity and dielectric constant. Full allowance is made for the anisotropy as a result of the Earth's geomagnetic field and for Earth curvature. The solutions to the mode equation are obtained by numerical integration of the reflection coefficients through the ionosphere. Field strength is computed by concatenating the segments and summing the wave guide modes using a mode conversion algorithm [*Pappert and Snyder*, 1972; *Pappert and Morfitt*, 1975].

The conductivity and dielectric constant of the Earth can be specified with some confidence over most paths [*International Radio Consultative Committee (CCIR)*, 1986]. Likewise, the magnitude and direction of the Earth's magnetic field are well known. The major problem lies in the assignment of parameters describing the ionosphere. The distribution of charged particles in the ionosphere depends in a complicated way on latitude, solar zenith angle, and season.

The ionospheric conductivity parameter ω_r is a function of the charged particle density divided by the particle-neutral collision frequency. One of the simplest ionospheric profiles is an exponential variation of conductivity with height. Following *Wait and Spies* [1964], this conductivity is taken to be

$$\omega_r = 2.5 \times 10^5 \exp[\beta(h - h')] \qquad (1)$$

where h is height, h' is the reference height, and β is the gradient in inverse height units. The value of the electron density N in electrons per cubic centimeter is calculated as a function of height as

$$N = 1.43 \times 10^7 \exp[\beta(h - h') - 0.15h] \qquad (2)$$

where β is in km^{-1} and h' is in kilometers. The collision frequency ν in collisions per second is assumed to be

$$\nu = 1.816 \times 10^{11} \exp(-0.15h). \qquad (3)$$

The usefulness of this simple exponential ionospheric conductivity model for computing VLF/LF fields is demonstrated by its success in modeling experimentally measured data for both daytime and nighttime propagation conditions [*Bickel et al.*, 1970; *Morfitt et al.*, 1981]. The modeling process consists of varying the values of β and h', calculating the field strength as a function of distance from the transmitter, and comparing the calculations with the measurements. This variation of ionospheric profile is continued until acceptable agreement between calculation and measurement is reached. In general, the ionospheric models so determined must be considered to represent an average ionosphere since the modeling assumes that the ionosphere was static during any measurement period. The drawback to this approach, given that the assumption of a temporarily static ionosphere is valid, is that only a single snapshot of the ionosphere results. Experience shows that this snapshot can change from hour to hour and day to day.

TABLE 1. Optimum Ionospheric Parameter Distribution for July

Parameter	Signal Statistics
r	0.80
β_0	0.38
σ_β	0.03
h_0	69.0
σ_h	0.20

SELECTION OF IONOSPHERIC PROFILES

Ferguson et al. [1985] applied a statistical model of the ionospheric parameters β and h' to data collected at Naples, Italy, and La Maddalena, Sardinia. In this model, β and h' were assumed to be distributed in a jointly normal distribution. Best fit values for this model were obtained using data obtained by monitoring the U.S. Navy's LF station located near Athens. The two sites are on either side of a deep modal interference null which occurs about 1000 km from the transmitter. The measured signal strength mean and standard deviation were used to obtain a best fit mean, standard deviation, and correlation coefficient for the distribution of β and h'. The optimum distribution of the ionospheric parameters yielded signal statistics that fit the measured mean and standard deviation at both monitoring stations to within 1 dB. The parameters of this fit for July are presented in Table 1, where r is the correlation coefficient, σ_β is the standard deviation of β, and σ_h is the standard deviation of h'. The parameters β_0 and h_0 are the mean values of β and h', respectively.

Because the ionosphere is continually changing during the day, the question arises as to which ionosphere should be used when predicting signal strength. A common approach is to use a single average ionospheric profile to predict the signal strength. The average signal strength at a particular location is not always the same as the signal given by the average ionosphere. The average ionosphere predicts the average signal strength quite well except in areas where there are large signal strength variations, such as near modal interference nulls.

To overcome some of the weaknesses associated with using a single average ionosphere to predict signal strength, multiple ionospheres were used in this work to include the effects of variation of the daytime ionosphere. Data were generated for β from 0.27 to 0.51 km^{-1} in increments of 0.02 km^{-1} and for h' from 64 to 78 km in increments of 0.5 km. Although the standard deviation of h' in Table 1 does not require such an extensive range of h', the data are useful for additional studies not reported here. It should be noted that the volume of data calculated for this study is only reasonable because the paths under consideration are all seawater and quite short. Because of the amount of computation involved, it would be very expensive to do such a study for long paths over which the ground conductivity changes frequently.

PATH PARAMETERS

The application of the propagation model to selection of transmitter frequency and power was done by generating calculations along two oppositely directed paths centered on a hypothetical transmitter site. The paths were arbitrarily chosen to form geographic bearing angles of 96° and 271° at the transmitter. Both paths are taken to be 2000 km long. The snr is the primary factor controlling the performance of a communication system. The propagation prediction program used in this study was used to calculate the signals along the two paths. The noise data were taken from the atmospheric noise model described by *CCIR* [1988] using July at 1600 UT. The signal strength and noise are assumed to be separate Gaussian distributions so that the snr is also Gaussian. For purposes of discussion the communications snr threshold is taken to be 0 dB. Satisfactory communications coverage is taken to occur when this threshold is exceeded 99% of the time.

Data were generated from 20 to 60 kHz in increments of 2 kHz. The snr as a function of distance for a radiated power of 1 kW for these frequencies is shown in Figures 1–4. The panels on the left of each figure show results for propagation to the east, and those on the right show results for propagation to the west. In each panel, two curves are shown. The data for these curves were calculated using the signal data computed from the matrix of profiles described above and weighted according to the Gaussian distribution parameters shown in Table 1. The solid curve represents the mean snr, and the dashed curve represents the snr which is exceeded 99% of the time. There is generally more than one minimum in the snr at each frequency. It is also apparent that the minima tend to move farther from the transmitter as frequency increases. As the minima move outward, their depths change. There is also a difference between eastward and westward propagation. It is evident in Figures 1–4 that frequency diversity can be used to mitigate the effects of nulls in critical areas by transmitting on frequencies chosen such that the positions of the nulls from the two transmitters complement each other.

CRITERIA FOR COVERAGE OF AN OPERATIONAL AREA

Ideally, a transmitter's radiated power requirement is based on providing satisfactory communications with a designated time availability throughout 100% of an area of interest. However, experience has shown that in the regions of modal interference nulls the signal level drops off to such a low level that very high transmitter power would be necessary to achieve coverage of 100% of the area of interest. Two schemes are considered: (1) coverage of 100% of the area and (2) coverage using a technique called "null smoothing." The solid curve (99% time availability) in Figure 5 is used to illustrate how the power requirement is determined using these schemes. Coverage of 100% of the area generally requires consideration of the snr at the maximum distance and at the locations of deep minima. In Figure 5 the curve representing a time availability of 99% has a value of −15 dB at the maximum distance and a value less than −40 dB in the null located near 700 km. Thus this coverage criterion requires radiation of 10 MW in order to raise the snr in the deep null to the communications threshold.

The second approach for establishing a transmitter's radiated power requirement is to use a technique referred to as "null smoothing." This technique ignores the small percentage of the area affected by deep signal nulls when determining the power requirement. Thus the minimum snr level outside of the region in which the most severe portion of the null occurs is used as the basis in determining the power requirement. The compromise made using this technique is that it is acceptable for a small percentage of the area not to be provided with satisfactory communications all of the time. The shaded region in Figure 5 corresponds to 5% (100 km) of the total distance. As a first

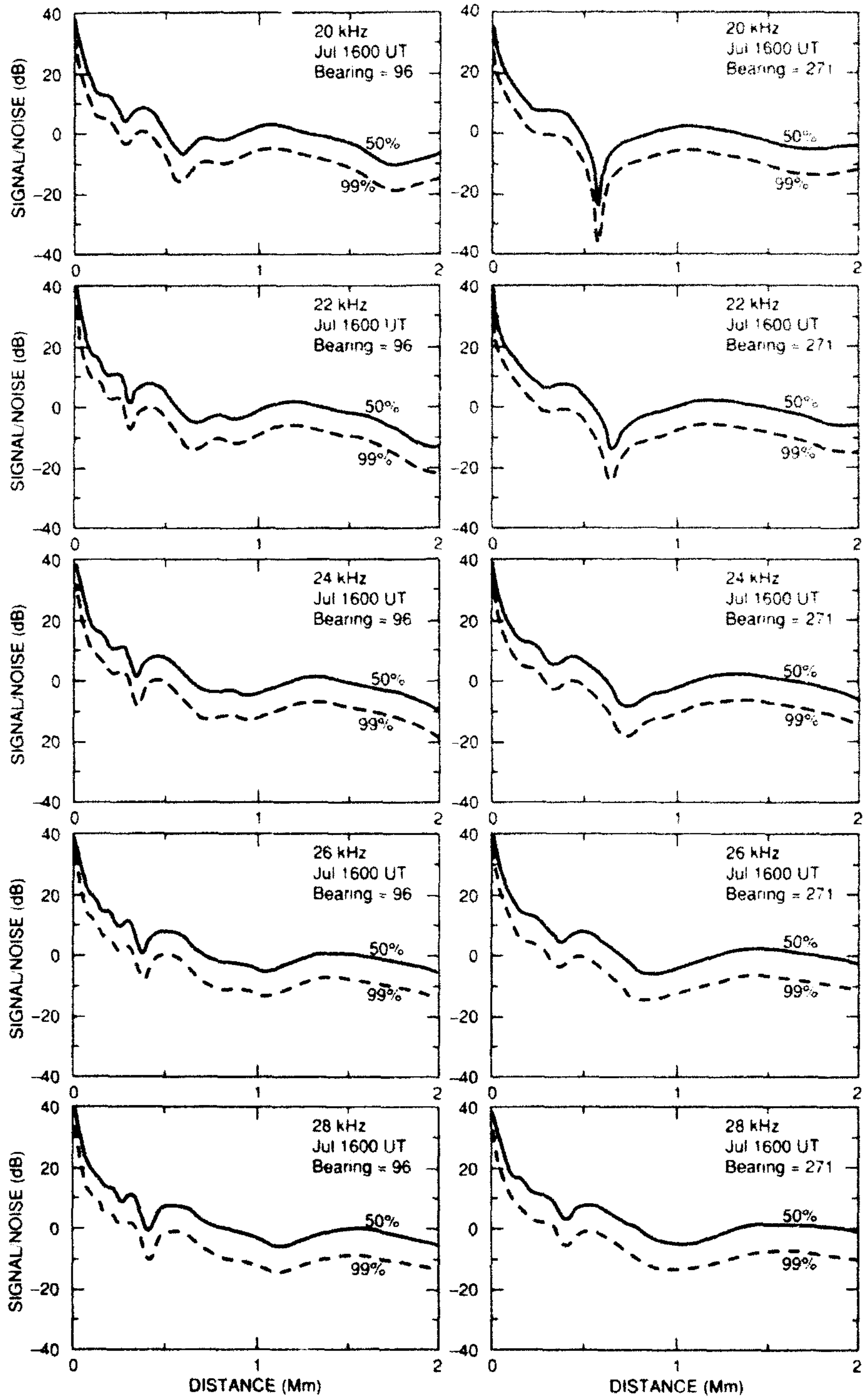

Fig. 1. Signal-to-noise ratio as a function of distance for the (left-side panels) west-east path and the (right-side panels) east-west path for 20–28 kHz.

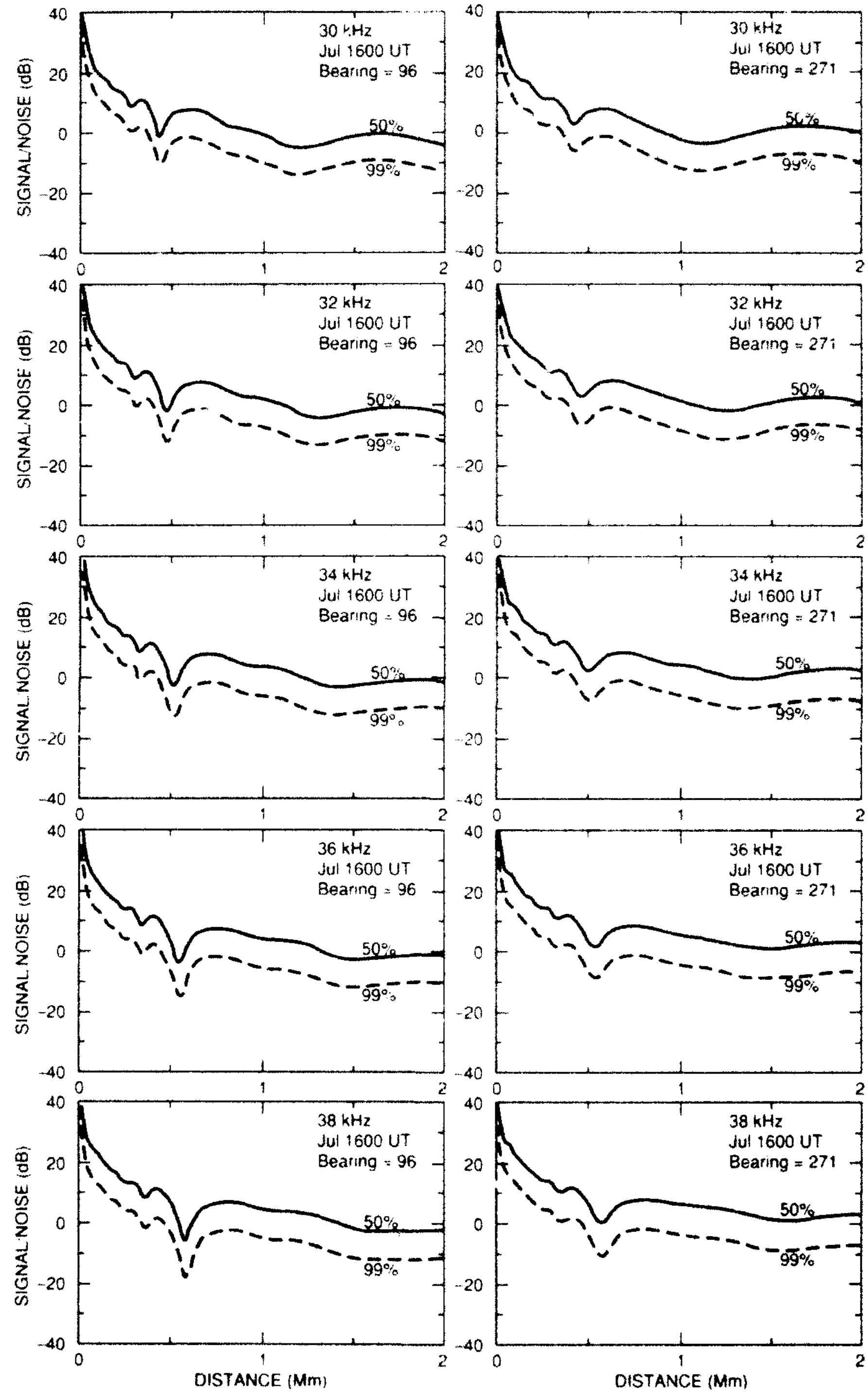

Fig. 2. Signal-to-noise ratio as a function of distance for the (left-side panels) west-east path and the (right-side panels) east-west path for 30–38 kHz.

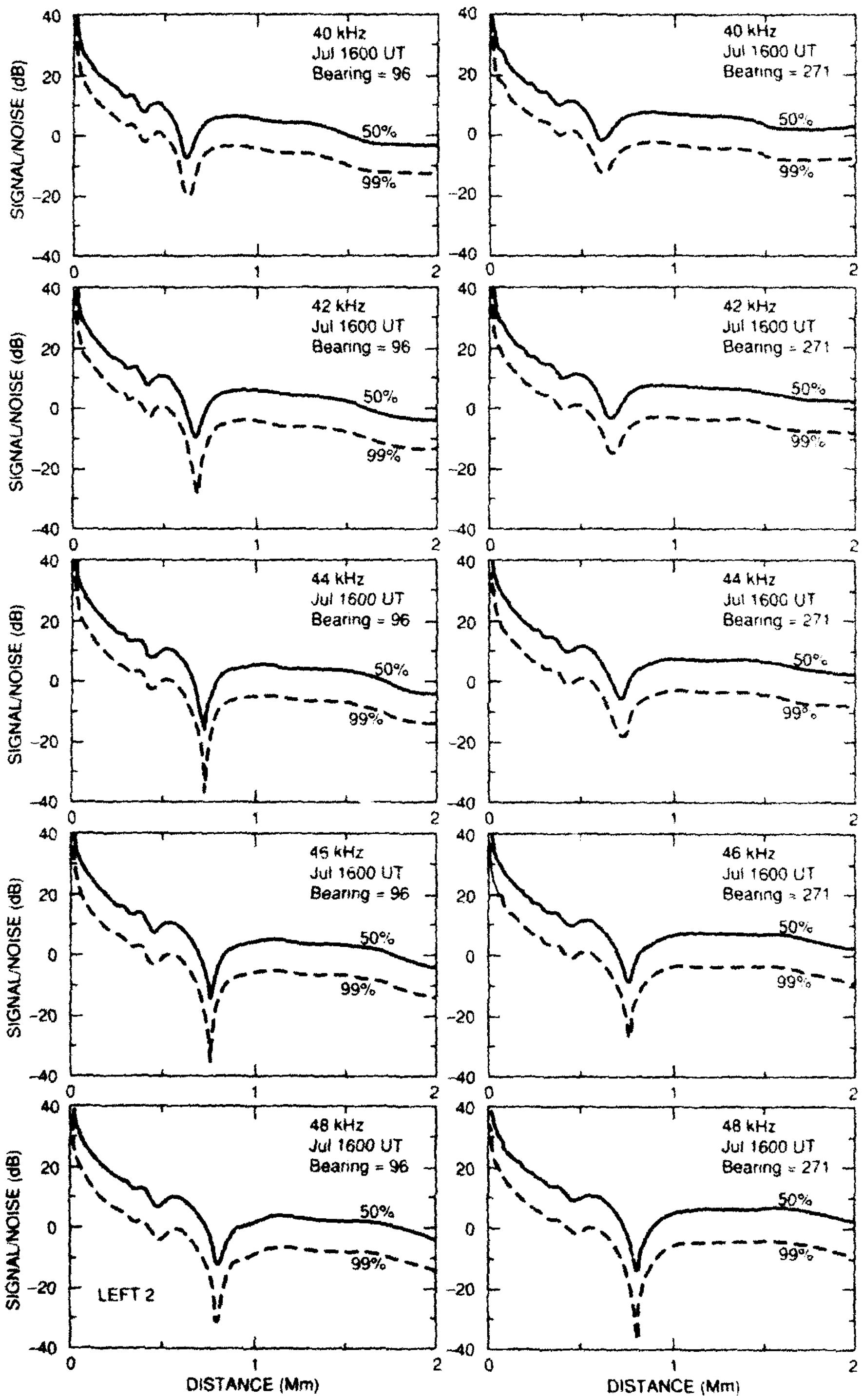

Fig. 3. Signal-to-noise ratio as a function of distance for the (left-side panels) west-east path and the (right-side panels) east-west path for 40–48 kHz.

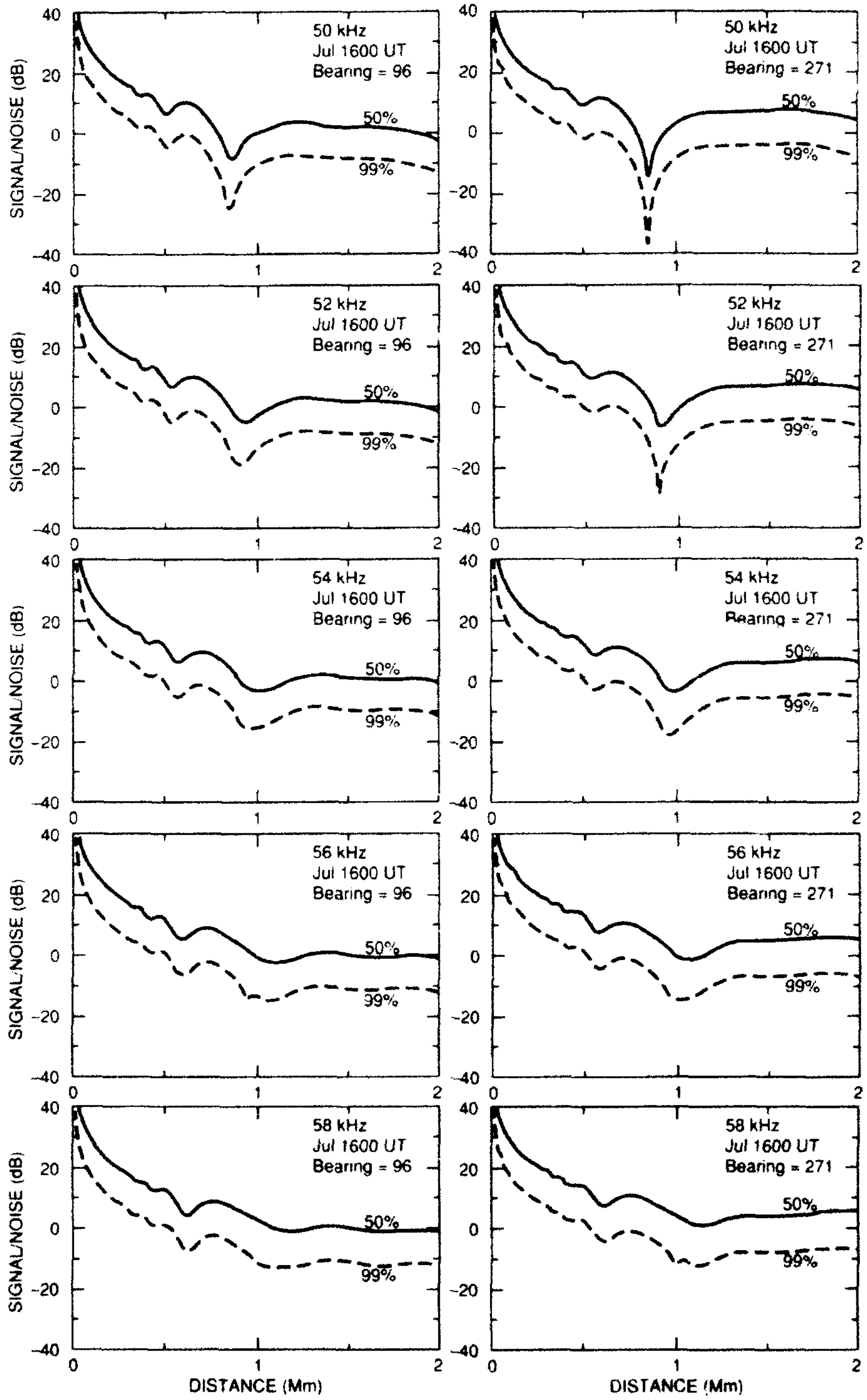

Fig. 4. Signal-to-noise ratio as a function of distance for the (left-side panels) west-east path and the (right-side panels) east-west path for 50–58 kHz.

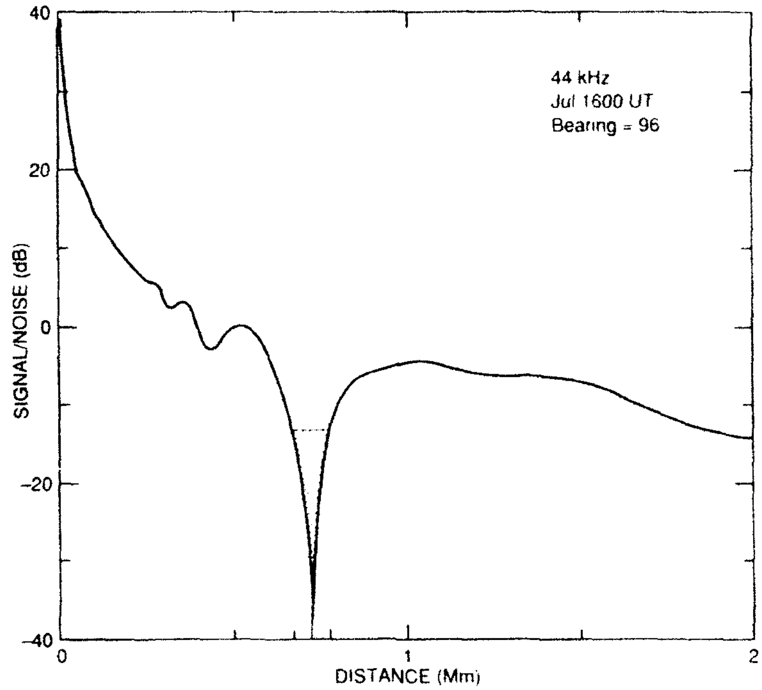

Fig. 5. Illustration of how the power requirement is determined with and without null smoothing.

approximation this percentage of the path length is taken to represent a corresponding percentage of the area which is not covered. (This is not a bad approximation in this case since the nulls of interest are in the range 500–1000 km from the transmitter. Taking the value to be 700 km, as in Figure 5, and making another crude approximation that the null sweeps out a ring about the transmitter, the area of the null is $2\pi \times 100 \times 700$, while the corresponding total area to be covered is $\pi \times 2000^2$. This makes the area of the null about 3% of the total area to be covered). Ignoring the shaded portion of the snr curve in the figure, the snr near the null is −13 dB. Basing coverage on the snr near the null and at the maximum distance results in the power requirement being determined by snr at maximum distance. The power requirement becomes 32 kW, 3 orders of magnitude below that required for coverage of 100% of the area.

RESULTS AND DISCUSSION

The power requirement as a function of frequency for the two coverage criteria is shown in Figure 6. This requirement is based on maintaining the snr above the threshold of 0 dB 99% of the time. The upper panel of Figure 6 is for the path to the east, and the middle panel is for the path to the west. In each of these panels there are five curves. The dotted curve shows the power required for coverage at the maximum range (labeled as "Max Range"). The data for the other curves were generated by choosing a minimum in the snr at 20 kHz and then following it from one frequency to the next. One pair of curves in each panel was obtained by following the shallow minimum near 250 km found in the curves for 20 kHz. The small solid circles connected by a solid line (labeled as "Min 1 100%") represent the power required for coverage of 100% of the area based on this minimum. The process of following the minima was repeated with application of null smoothing on the same sequence of minima. This third curve is delineated by the small solid circles enclosed by larger circles connected by a solid line (labeled as "Min 1 95%"). Another pair of curves, shown using crosses and a dashed line (labeled "Min 2 100%" and "Min 2

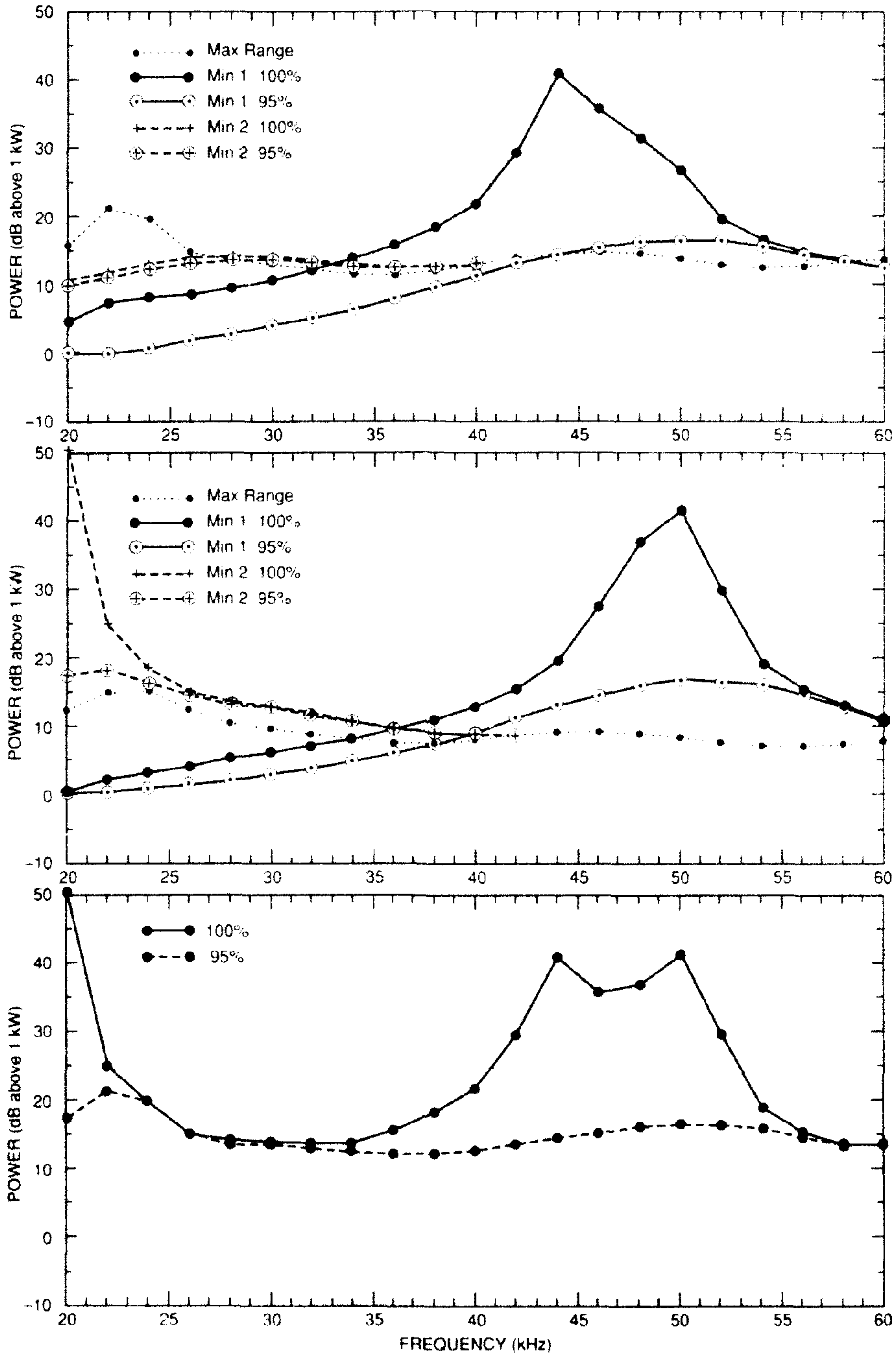

Fig. 6. Power requirement as a function of frequency for (top) the west to east path, (middle) the east to west path, and (bottom) combined.

95%''), was generated starting with the minimum found at about 600 km in the curves for 20 kHz.

The power required for coverage of the area at each frequency is obtained by taking the maximum of the power required for both directions. This result is shown in the bottom panel of Figure 6 in which the solid curve is for 100% coverage and the dashed curve is for 95% coverage (based on null smoothing). For 100% coverage the power requirement is below 100 kW between 24 and 39 kHz and above 54 kHz. It is below 30 kW between 26 and 34 kHz and above 56 kHz. The minimum power requirement is 22 kW at 32 kHz. Coverage of 95% of the area is obtained with a power requirement below 50 kW for all frequencies above 25 kHz with a minimum of 18 kW at 38 kHz.

The selection of frequency and power for a transmitting station is a complicated task involving trade-offs between the engineering and cost factors and the requirements for acceptable communications and time availability. Designing to a worst case is usually unsatisfactory in the light of the uncertainties in signal variability at low frequencies. A more reasonable approach is to accept *slightly less than 100% coverage of an area.* It remains to evaluate by process of measurement and modeling the overall impact of this approach.

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